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RESEARCH MEMORANDUM

COMBUSTION PROPERTIES OF ALUMINUM AS RAM-JET FUEL

By J. Robert Branstetter, Albert M. Lord, and Melvin Gerstein

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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SUMMARY

An experimental investigation was conducted to determine the combustion properties of aluminum as a fuel for use in high-speed aircraft. The aluminum fuel was injected both in powder and wire form into 2-inch-diameter ram-jet-type combustors.

Steady combustion was obtained with the aluminum injected in powder form although the thrust was less than that obtained by burning propane at equivalent conditions. The decreased thrust was partly attributed to reduction of nozzle area and to friction losses resulting from aluminum-oxide deposits.

The aluminum wire could be atomized and burned stably with combustion efficiencies of about 75 percent at a combustion-chamber-inlet velocity of 115 feet per second. The investigation covered a range of fuel-air ratios from 31 to 92 percent of stoichiometric.

INTRODUCTION

An investigation of the possible use of metals as fuel for ram-jet-powered aircraft is being conducted at the NACA Lewis laboratory. The interest in metals as fuels arises from the necessity to extend range, thrust, and operating limits of supersonic aircraft. From the results of an initial study, presented in 1947 (reference 1), aluminum was chosen as one of the metals on which combustion experiments would be concentrated. Other investigations that were conducted to study the use of aluminum as a jet-engine fuel are reported in references 2 to 4.

The flight range and the thrust attainable with various types of fuel are dependent upon the following thermodynamic properties:

(1) Heat of combustion per unit weight

(2) Heat of combustion per unit volume

(3) Flame temperature

(4) Momentum change of fuel mass 2105

(5) Mean molecular weight of exhaust gases

(6) Latent heats of fusion and vaporization of exhaust products

(7) Ratio of specific heats

(8) Temperature and velocity relations between exhaust gases and solid and liquid oxides

(9) Molecular relaxation time for exhaust gases

Several of these factors are of particular interest; those most indicative of flight range are the heats of combustion. A comparison of the heating values for several fuels is given in the following table:

Fuel	Gross heats of combustion		
	(Btu/lb)	(Btu/cu ft)	Reference
Hydrogen	61,085	[a]270,190	5
Diborane	33,513	[a]935,200	6
Pentaborane	30,175	[b]1,149,000	7
Beryllium	26,941	[c]3,055,000	5
Boron	23,281	[c]3,372,000	5
Gasoline	[d]20,000	[b,d]900,000	
Graphite	14,126	[c]1,991,000	5
Aluminum	13,320	[c]2,243,000	8
Magnesium	10,813	[c]1,174,000	5

[a]Refrigerated liquid.
[b]Based on density at standard atmospheric conditions.
[c]Maximum solid density.
[d]Approximate.

Substantial gains in the heats of combustion as compared with gasoline can be attained for fuels such as beryllium, boron, and boron hydrides in regards to both weight and volume.

In determining the specific thrust of a ram-jet fuel, the most important single property is flame temperature. Because the literature on flame temperatures of the metal fuels is incomplete, the heating values per unit weight of air at stoichiometric, which are roughly indicative of the flame temperature, for several fuels are presented in the following table:

Fuel	Stoichiometric fuel-air ratio	Heat of combustion (Btu/lb air)
Magnesium	0.353	3820
Beryllium	.130	3500
Aluminum	.261	3480
Boron	.105	2440
Diborane	.067	2250
Hydrogen	.0292	1780
Gasoline	.067	1340

Flight range and thrust are also dependent on other factors that are related to the fuel; for example, both the fuel-handling system and the combustor must be engineered for satisfactory utilization of the fuel with minimum aerodynamic losses. In addition, for other than the simplest of flight plans, stable and efficient combustion must occur over a wide range of combustor-inlet conditions. An experimental evaluation of the operational limits of a fuel and combustor combination are necessary for this determination. An investigation of diborane is reported (reference 9) in which diborane gave longer range, higher thrust, and more stable operation than conventional fuels.

In order to determine stability, efficiency, and kinetic energy release of a metal fuel, an experimental evaluation of aluminum was made in small ram-jet-type combustors. Aluminum was selected because of its availability and relative ease of handling, and because it is believed that the problems inherent with its use are indicative of the problems with other metal fuels.

Although the operational limits of a fuel are dependent on combustor design, chemical kinetic considerations such as flame-propagation rate are indicative of trends to be expected. Some flame-propagation data are available for aluminum. For example, the rate of flame movement through clouds of aluminum powder and air is of the same order of magnitude as that of hydrocarbon-air mixtures (reference 10). The limits of inflammability of aluminum indicate that aluminum powder mixed with air can support a flame at atmospheric temperature and pressure in fuel-air ratios as lean as 12 percent of stoichiometric (reference 11). The ignition temperature ranges from 585° to 700° C depending on particle size (reference 11). These values indicate that the aluminum-powder reactions are similar to hydrocarbon reactions.

In order to ascertain the nature of the combustion problems encountered with aluminum, two techniques of injection were tried. One method utilized aluminum powder; the other utilized aluminum wire. The discussion of each method is treated separately. This exploratory investigation was conducted during 1948 and 1949. 2105

INVESTIGATION OF POWDER COMBUSTOR

Apparatus

The combustion chamber consisted of a section of stainless-steel tubing $1\frac{7}{8}$ inches in internal diameter, 30 inches long, and a nozzle that had an exit diameter of $1\frac{1}{4}$ inches. Illustrations of the combustor and powder injection-tube assembly are presented in figure 1. The cooling-water trough contained approximately 40 pounds of water, which was agitated by a propeller. Combustion air at room temperature was supplied by a blower, the maximum pressure of which was 3.5 inches of mercury gage; air flow was measured by an orifice conforming to A.S.M.E. standards. The ignition source was a flush-mounted gunpowder squib that burned for 4 seconds. An oscillating flame holder that consisted of a 3/8-inch-diameter water-cooled shaft was used. The flame holder was driven back and forth, normal to the flow, through close-fitting guides to prevent build-up of aluminum oxide.

The powder, contained in a $1\frac{1}{8}$-inch-diameter injection tube, was forced into the combustion chamber by means of a piston. The rate of piston travel was used to measure powder flow. The somewhat irregular powder density throughout the length of fuel tube affected the accuracy of fuel-flow measurement.

In order to facilitate mixing of the powder and the air, the powder was forced through a rapidly rotating slotted disk (fig. 1(b)). The disk also served to prevent the air stream from aspirating the powder into the combustion chamber during starting operations.

For purposes of comparison, a propane fuel system was also installed. The fuel orifices were located approximately 1 foot upstream of the aluminum injector tube. For propane runs, an annular-type flame holder blocking 30 percent of the combustion chamber was used to stabilize the burning.

The jet thrust developed was measured by means of a disk-type thrust target shown in figure 1(b). The force on the target was transmitted to strain gages and the electric impulse was read on a potentiometer. The thrust-measuring apparatus was calibrated by dead loading with weights and by blasting air against the target. An estimated experimental error of 5 percent existed in the thrust apparatus at the test conditions.

Procedure

The fuel mixture was 75-percent atomized, 200-mesh aluminum and 25-percent flaked aluminum by weight. A 3/4-pound charge was poured into the injection tube and compressed by use of a vibrator to obtain a uniform density. The fuel tube was then attached to the combustor; the air flow in the combustor was set to about 30 feet per second; and the cutter blade and piston were energized. When a cloud of powder and air emerged from the nozzle, the mixture was ignited by a gunpowder squib. As soon as the flame stabilized in the combustion chamber, the air-flow rate was adjusted to the experimental value. The rate of piston travel was held constant for any single run. The fuel-tube capacity limited the runs to only 1 minute. Data were recorded near the end of the run in order to permit data to be taken as near equilibrium as possible.

Results and Discussion

Operational problems. - The apparatus became white hot after 5 to 10 seconds of burning and burned through after 20 to 25 seconds if the combustion chamber was not placed in a cooling trough. Any metal or ceramic parts such as thermocouples, spark electrodes, or flame holders soon failed unless these parts were protected by cooling.

The rapid failure of the electrodes was one of the reasons for the adoption of a gunpowder squib as an ignition source although a spark from a 10,000-volt transformer was sufficient to ignite the mixture. Another reason for the rejection of electrodes as an ignition source was the accumulation of unburned powder and the solid products of combustion on the electrode surfaces. The use of flush-mounted gunpowder squibs eliminated these obstructions.

Thermal failure and the accumulation of solids on exposed surfaces presented a problem in the choice of a flame holder. Several types of flame holder were investigated during the course of the research. If spark ignition was used, no additional flame holder was required, because the electrodes and the deposits that accumulated about them early in the run blocked sufficient area to act as a flame stabilizer. When ignition was accomplished by means of a gunpowder squib, flame stability could not be achieved without a flame holder. 2105

An annular-type flame holder (fig. 2(a)), which blocked about 30 percent of the cross-sectional area of the combustion chamber, supported stable burning for either aluminum powder or propane. This flame holder proved to be impractical for aluminum combustion, however, because of the rapid accumulation of deposits on it. A photograph of the annular flame holder after a 30-second run with aluminum is shown in figure 2(a). In order to reduce the accumulations of deposits on the flame holder and to prevent failure due to melting of the metal, a water-cooled shaft that could be pulled back and forth through close-fitting guides was used. The shaft of the oscillating flame holder had a stroke of 3 inches and was driven at 20 cycles per minute. This system, although not entirely successful, did markedly reduce the accumulation of solids.

Originally, the exhaust nozzle was attached to the combustion chamber by flanges and any slight misalinement of the two sections caused excessive oxide deposits. Subsequent nozzles were formed by fabricating the nozzle and the combustion chamber from the same piece of material in such a manner that smooth transition was attained.

In the apparatus that resulted from this developmental work, the oxide build-ups were sufficient to form an uneven coating, approximately 1/8 inch thick, along the walls and the nozzle. Undoubtedly, runs of longer duration would have produced thicker deposits than those obtained with a 1-minute run. Some of the solids were blown out from time to time as evidenced by figure 2(b), which is one frame of a motion picture taken at 2000 frames per second.

<u>Thrust.</u> - A brilliant white flame existed for a short period following ignition (fig. 3(a)). As the combustor temperature rose, the flame receded into the nozzle until a much smaller and well-defined flame formed (fig. 3(b)).

Measurements with an optical pyrometer of the near stoichiometric flames showed temperatures in excess of 4800° R. No correction was applied for deviation from black-body conditions.

Heat rejection to the cooling water as measured by temperature rise was 20 to 30 percent of the potential heat release of aluminum. Although the heat loss to the bath was not measured for propane combustion, the rate of loss was estimated to be considerably lower than for aluminum.

Thrust and air-flow measurements plotted as functions of simulated flight Mach number are presented in figures 4(a) and 4(b). Similar data for propane in the same combustor but using an annular flame holder are shown for comparison. The data for aluminum include fuel-air ratios from 60 to 120 percent of stoichiometric (stoichiometric for aluminum is 0.26); data for propane cover a range of 80 to 125 percent stoichiometric (stoichiometric for propane is 0.066). The conversion of combustor-inlet pressures to simulated sea-level flight velocities was made assuming isentropic compression. Combustion-air velocities ranged from 25 to 55 feet per second. The range of simulated flight Mach numbers shown in figure 4 is below the range of interest for practical flight utilization of ram-jet engines. Nevertheless, this method of plotting was used in order to illustrate the data trends and to show the effect of oxide deposits. The air-supply system used established the particular inlet-air conditions.

The broken line in figure 4(a) shows values of theoretical jet thrust based on ideal air-cycle analysis and assuming isentropic processes. The theoretical jet thrust is independent of combustor temperature rise and is given by the following equation:

$$F_j = p\gamma AM^2$$

where

F_j jet thrust, (lb)

p atmospheric pressure, (lb/sq ft absolute)

γ ratio of specific heats

A nozzle-exit area, (sq ft)

M flight Mach number

The curve showing values of F_j obtained with aluminum is about 40 percent lower than the curve for propane. Less than 5 percent of this difference can be attributed to differences in γ for the exhaust products obtained with the two fuels. The remaining 35 percent must be accounted for by internal friction losses above those encountered with propane and by reduction of the exhaust-nozzle area. Both of these effects are due to formation of the solid deposits on the walls of the combustion chamber and exhaust nozzle.

Net thrust and net specific thrust are presented in figures 4(c) and 4(d) as functions of flight Mach number. These curves were calculated directly from the curves faired through the data of figures 4(a) and 4(b).

The lower net thrust for aluminum, relative to the propane-fueled combustor, is contrary to expectations based on fuel-mass increase and flame temperature. The most obvious reasons for this reversal are, as with jet thrust, internal friction and reduction of exhaust-nozzle area due to deposits. At very low flight speeds, performance is highly sensitive to pressure losses within the combustor (reference 12). Furthermore, combustion efficiency for the aluminum was generally lower than for propane.

Combustion-efficiency data for aluminum are presented in figure 4(e) as a function of burner-inlet velocity. The efficiency is given by the equation

$$\eta_{b,t} = \frac{T_o - T_i}{T_{id} - T_i} \times 100$$

where

$\eta_{b,t}$ combustion efficiency computed from temperature-rise ratio, percent

T_o nozzle-outlet temperature, ^{o}R

T_i combustion-chamber inlet temperature, ^{o}R

T_{id} ideal outlet temperature, ^{o}R

Outlet temperature T_o was calculated from the ideal equation of state with the velocity term determined from measured jet thrust. Any corrections for heat transfer would have increased $\eta_{b,t}$. Without this correction the average of the data points is approximately 50 percent.

INVESTIGATION OF WIRE COMBUSTOR

Apparatus

A commercial metalizing gun was so modified that gas-flow measurements could be made and the atomizing nozzle could be sealed to the combustor inlet. A sketch illustrating the construction and the operation of the wire atomizer is shown in figure 5. The gun uses an oxygen-propane flame to melt the wire, then a jet of air to atomize it; 3/16-inch-diameter wire was driven into the atomizer by an air motor controlled by a speed governor. A tachometer indicated the wire speed. Flowmeters measured the oxygen, the propane, and the atomizing and secondary air. The temperatures of the entering air, oxygen, and propane were measured with thermometers. The temperature of the wire was assumed to be that of the ambient air.

The combustion chamber was made of 2-inch stainless-steel, standard wall pipe 12 inches long. A taper was cut in the inside of the inlet end to effect a seal with a rubber O-ring in the atomizer head. The combustion chamber was welded to a double-walled jacket containing a salt that melted at 800° F in the inner chamber and flowing water in the outer chamber (fig. 6). The water jacket also cooled the rubber seal in the atomizer head and a thermocouple measured the outer-wall temperature of the combustion chamber.

The combustor discharged into a plenum chamber, which was sealed to the combustor with a sponge-rubber gasket. The plenum-chamber cover could be removed or replaced while the combustor was operating. Nozzles filled the chamber with a dense water spray to cool the gases. The water drained through a gas trap. A baffle prevented the entrainment of water droplets in the exhaust gas. A photograph of the assembly is shown in figure 7. The temperatures of the gas and the water leaving the plenum chamber were measured by thermocouples so that a heat balance could be obtained.

Procedure

In a typical run, the water flow was started through the outer cooling jacket; the oxygen, propane, and atomizing-air flow started; and the propane ignited by means of a hand torch inserted into the combustion chamber. After a 10-minute warm-up period, the salt coolant had melted. When the combustion-chamber wall temperature reached about 1250° F, the secondary air and the wire-drive motor were started and set to give a metal-air ratio of about 0.2. A gunpowder squib was inserted into the combustion chamber to ignite the spray. The squib had to be held in the combustion chamber until the walls were coated with an incandescent oxide deposit, otherwise the aluminum flame would die out. The fuel-air ratio was then adjusted by changing the wire speed. When stable burning was achieved, the water sprays were turned on in the plenum and the plenum was covered. Data were recorded when the temperatures of the exhaust gas and the water from the plenum reached equilibrium.

The combustion efficiency of the aluminum was calculated by the equation

$$\eta_b = \frac{h_o - h_i - H_p + Q}{H_{al}} \times 100$$

where

η_b combustion efficiency

h_o enthalpy of exhaust gas, solid combustion products, and water leaving plenum, (Btu/hr)

h_i enthalpy of inlet air, oxygen, propane, aluminum, and water, (Btu/hr)

H_p heat of combustion of propane, (Btu/hr)

Q estimated heat loss of system, (Btu/hr)

H_{al} heat of combustion of aluminum, (Btu/hr)

The heat of combustion of propane was taken as 21,650 Btu per pound (reference 13) and of aluminum as 13,320 Btu per pound. The following assumptions were made:

(a) The propane burned completely.

(b) The composition of the combustion products was that which would result from completely burned aluminum and propane.

(c) The exhaust gas was saturated with water vapor but carried no water droplets.

(d) The aluminum oxide left the plenum chamber at the same temperature as the water.

Thermodynamic data for the enthalpies of oxygen, nitrogen, and water vapor were taken from reference 14; data for the enthalpies of propane, aluminum, and aluminum oxide came from reference 13; and the enthalpy of water was taken from reference 15. The estimated heat loss of the system was approximately 3 percent of the heat input.

Results and Discussion

Operational problems. - The spray of aluminum and air in the combustion chamber was difficult to ignite. An outside combustion-chamber-wall temperature of 1100° F was required for ignition. The high velocity of the metal particles issuing from the atomizing nozzle is believed to make preheating of the combustion chamber necessary before ignition is possible. High combustion-chamber wall temperatures were needed to maintain combustion. The proper wall temperature was obtained by using a double-jacketed combustor containing molten salt in the inner chamber and water in the outer chamber (figs. 6 and 8). Thus, the combustion-chamber wall could be protected from overheating without lowering the temperature to the point where flame failure would occur.

The high wall temperatures required by this system imposed a materials problem, particularly at high fuel-air ratios. A typical failure is illustrated in figure 8. After the run, the combustor was cleaned and cut through at the point of failure. The spot where the combustion-chamber tube melted and the point at which some of the molten salt leaked into the combustion chamber to give the first indication that the wall had failed can be seen.

The failure of combustor materials can be attributed to at least two causes: (1) The flame temperature of aluminum-air mixtures is estimated in excess of 6000° R; (2) most high-temperature alloys, particularly those containing nickel, are extremely soluble in molten aluminum.

Within the combustion chamber, the deposits were often 1/4 inch thick after a 10-minute run. Examination after the plenum was removed showed little internal growth of deposits after 5 minutes. By this time a thermal barrier of sufficient resistance had been established to permit melting of the oxide that impinged on the wall. The molten oxide flowed along the surface to the exit, solidified as it came in contact with the air, and formed a clinker protruding beyond the nozzle exit. This clinker often deflected the jet upwards.

Oxide deposition can be somewhat controlled by operating the combustor at the maximum permissible wall temperature. Also, combustors currently considered for flight application are sufficiently larger than the 2-inch combustors discussed herein that the relative effect of oxide deposition on performance would be reduced. The uneveness and unpredictability of oxide deposition, however, necessitates additional control of oxide build-up. Several recourses are of interest.

Sweat-cooling with water through porous-bronze nozzle walls (reference 4) has eliminated oxide deposits of flaked aluminum and air flames. Also, a ceramic surface that can withstand thermal shock and can be maintained at temperatures higher than that of the fusion temperature of the oxide should reduce deposits. Deposition problems may be eliminated when certain metals, such as boron, that have a low melting oxide are burned.

Combustion efficiency. - Combustion was stable in the wire combustor although no flame holder was used. Inlet velocity computed on the basis of atmospheric pressure in the combustor, uncoated chamber walls, and the mixture of the oxygen-propane flame products and the combustion air at 3000° F was 115 feet per second. The products of the propane flame diluted the combustion air by about 20 percent.

Combustion efficiencies plotted as a function of fuel-air ratio are shown in figure 9. The data cover a range of fuel-air ratios from 31 to 92 percent of stoichiometric. The efficiency was almost constant at about 75 percent from fuel-air ratios of 0.08 to 0.20. The fuel-air ratio was varied by changing the wire speed and hence the fuel-air ratios in figure 9 are directly proportional to wire speed. The metal spray becomes coarser as wire speed is increased; this fact may account for the slight decrease in efficiency at high fuel-air ratios. The maximum wire speed and the fuel-air ratio were limited by the permissible feed rate of the atomizing gun.

SUMMARY OF RESULTS

The following results were obtained in an experimental investigation to determine the combustion properties of aluminum as a fuel for use in high-speed aircraft. The aluminum fuel was injected both in powder and wire form into 2-inch-diameter ram-jet-type combustors.

1. Stable combustion was obtained with aluminum injected in powder form although the thrust was less than that obtained by burning propane at equivalent conditions.

2. Over a range of fuel-air ratios from 31 to 92 percent of stoichiometric, aluminum wire was stably burned with combustion efficiencies of about 75 percent at a combustor-inlet velocity of 115 feet per second.

3. Solid deposits in the combustion chamber present a serious obstacle to the utilization of aluminum as a ram-jet fuel.

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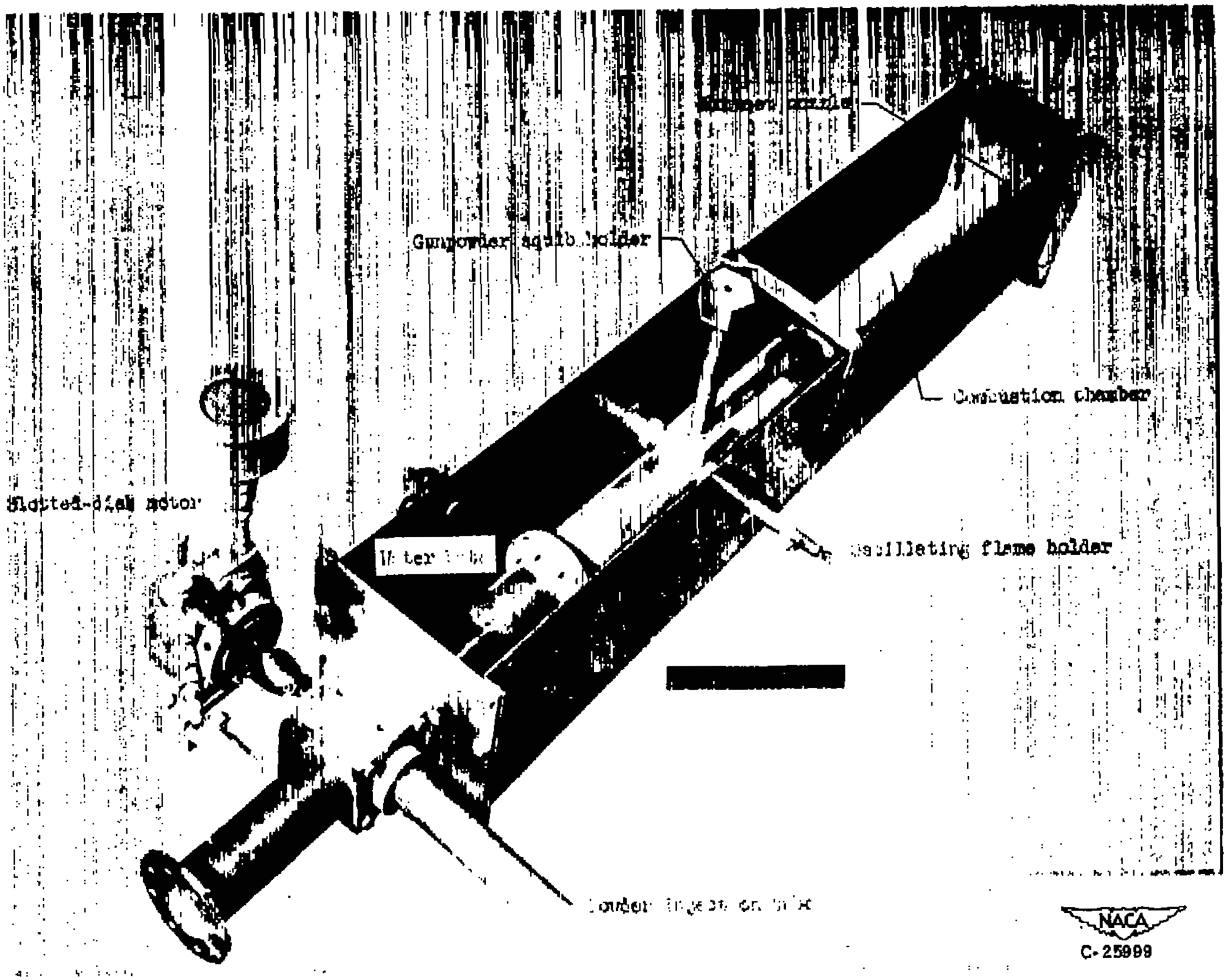
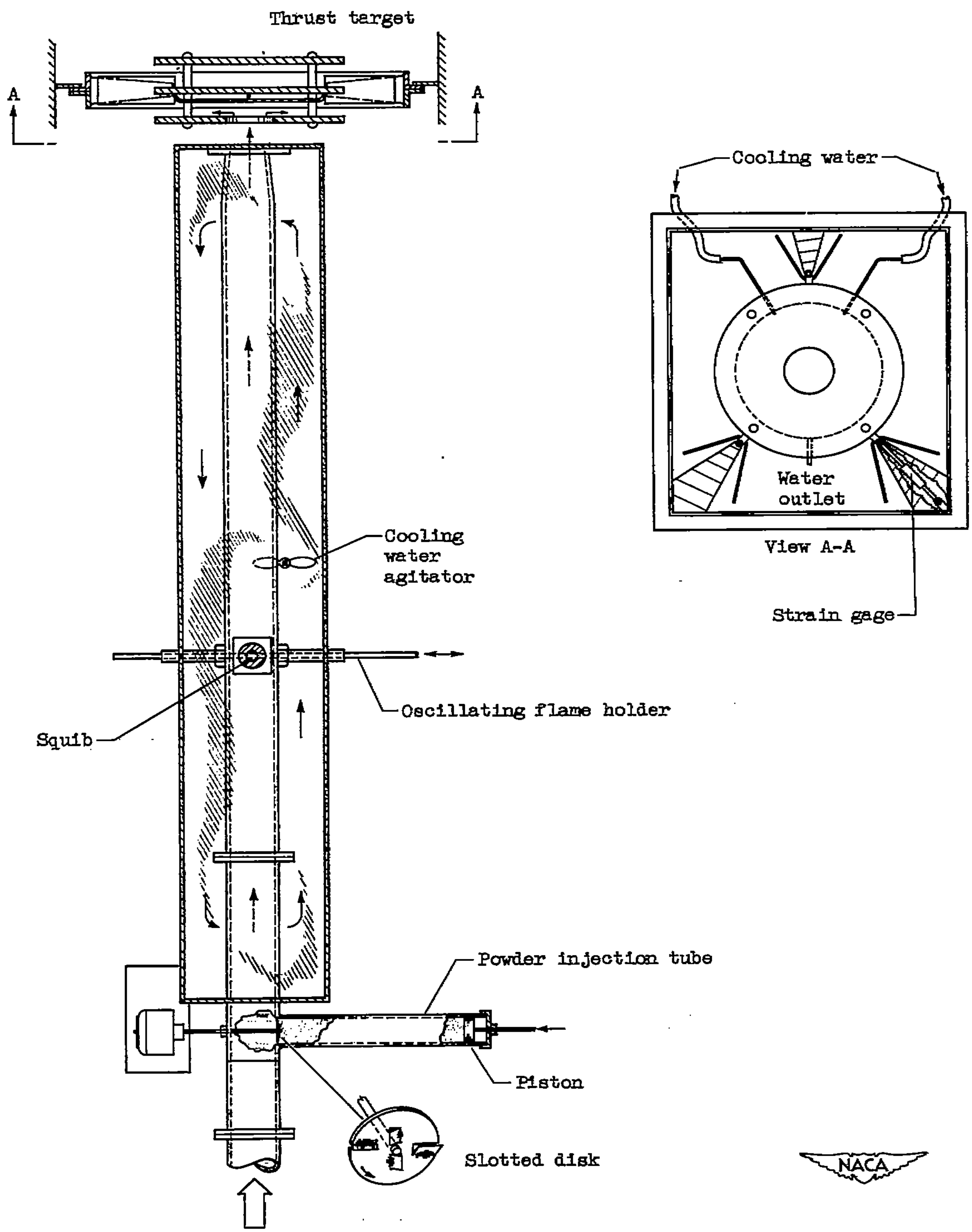


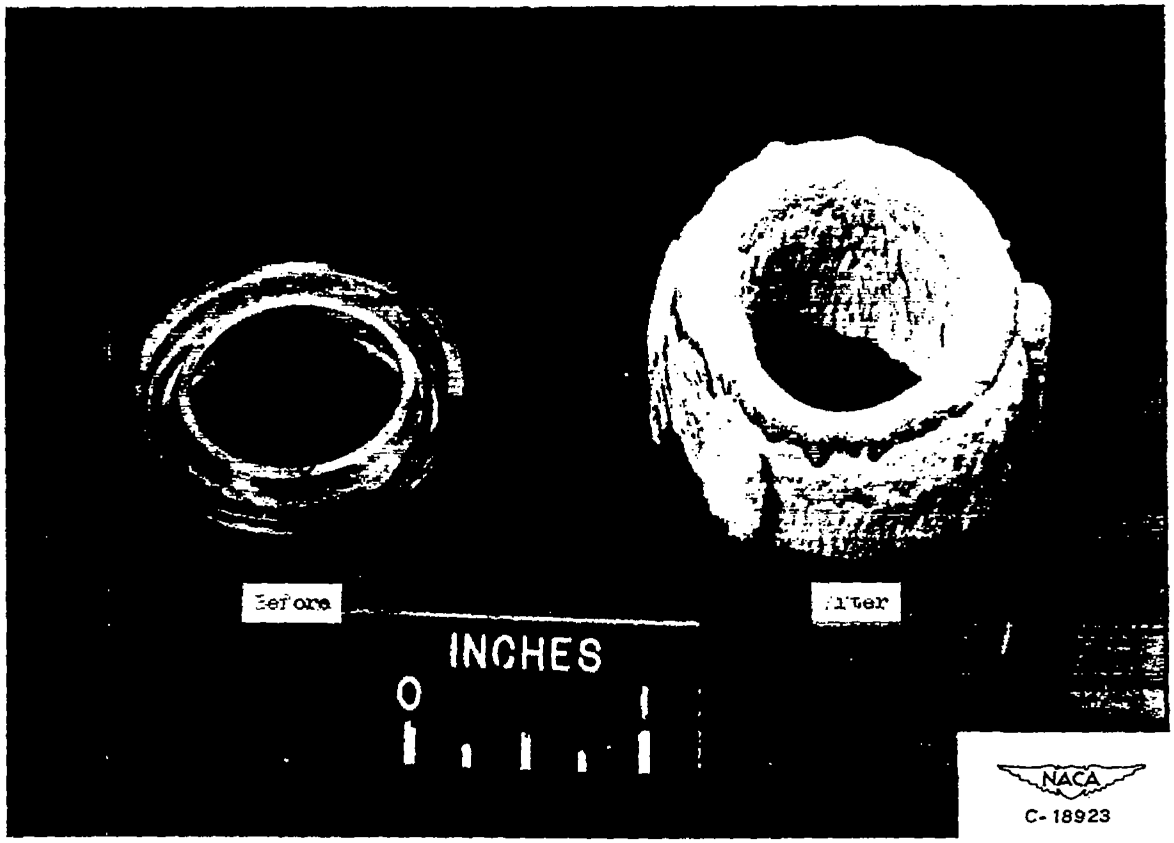
(a) Over-all view of powder combustor.

Figure 1. - Experimental setup for 2-inch powder combustor.



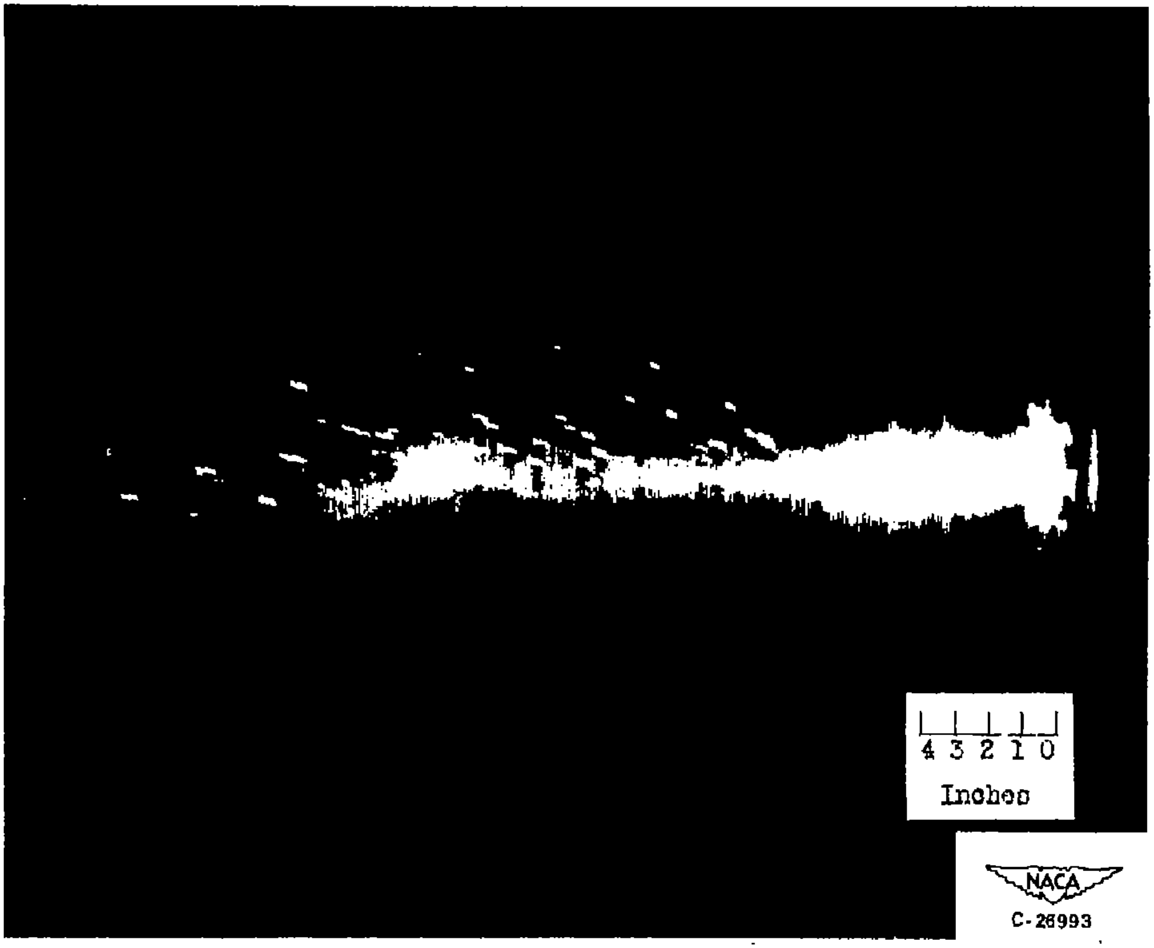
(b) Powder combustor and thrust target.

Figure 1. - Concluded. Experimental setup for 2-inch powder combustor.



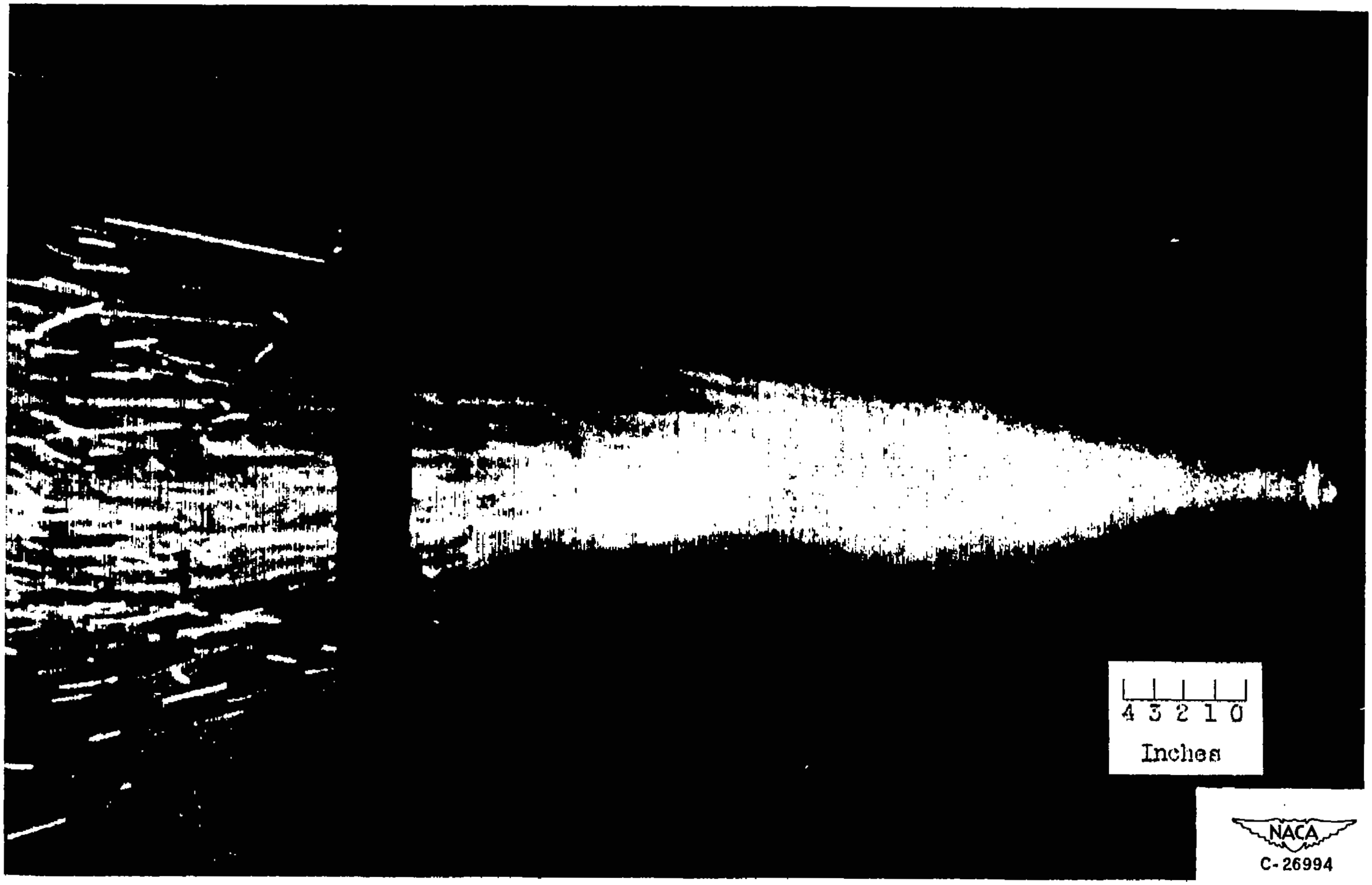
(a) Annular-type flameholder before and after 30-second run.

Figure 2. - Solid deposits that result from combustion of powdered aluminum.



(b) Solid deposits being blown from powder combustor. (Enlargement of motion picture taken at 2000 frames/sec.)

Figure 2. - Concluded. Solid deposits that result from combustion of powdered aluminum.



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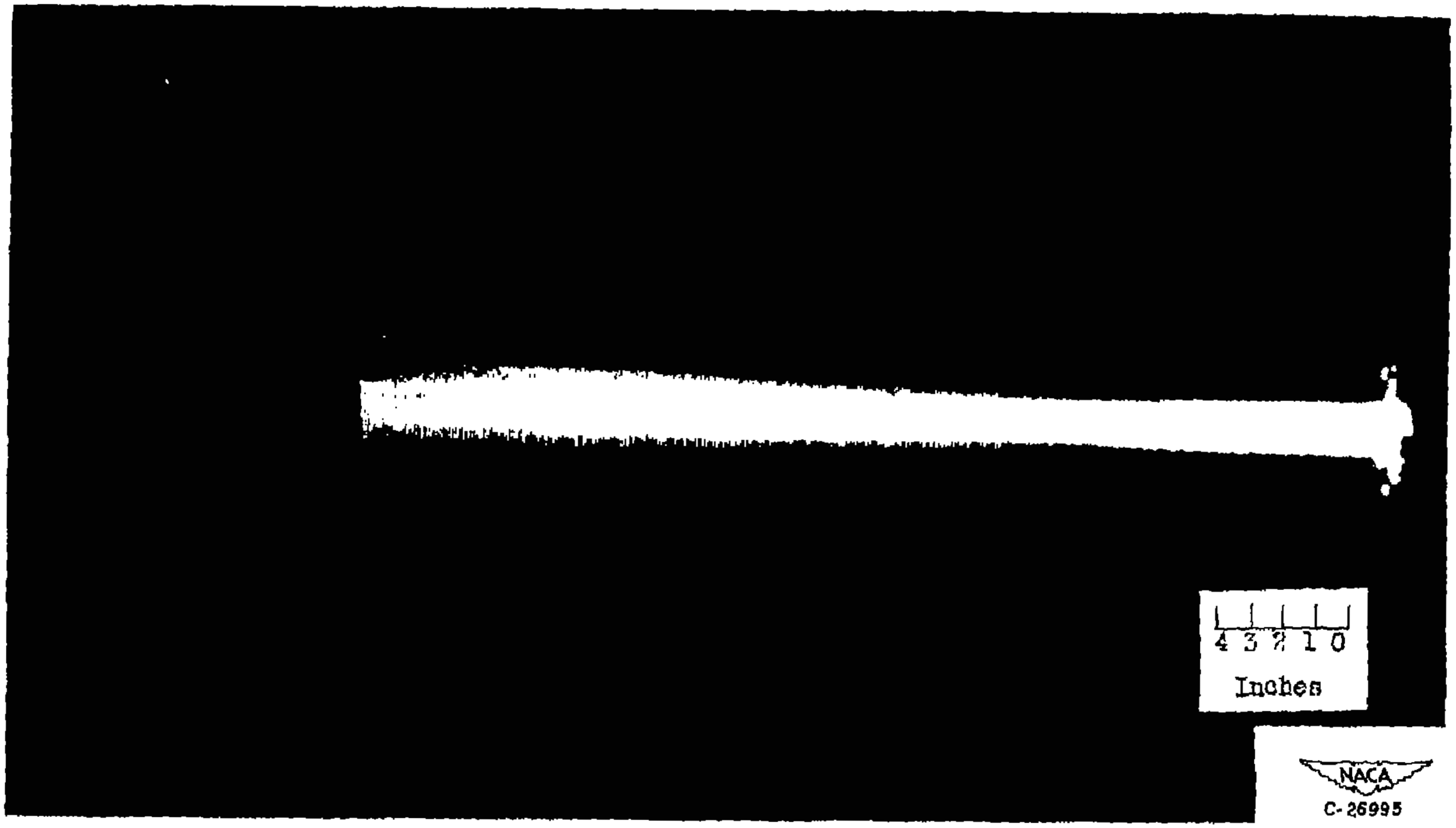
(a) Flame immediately after ignition.

Figure 3. - Flame emitted from combustor.



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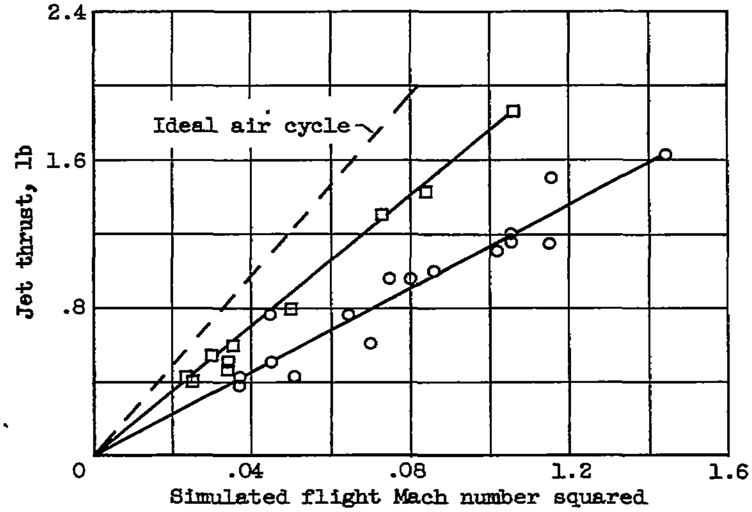
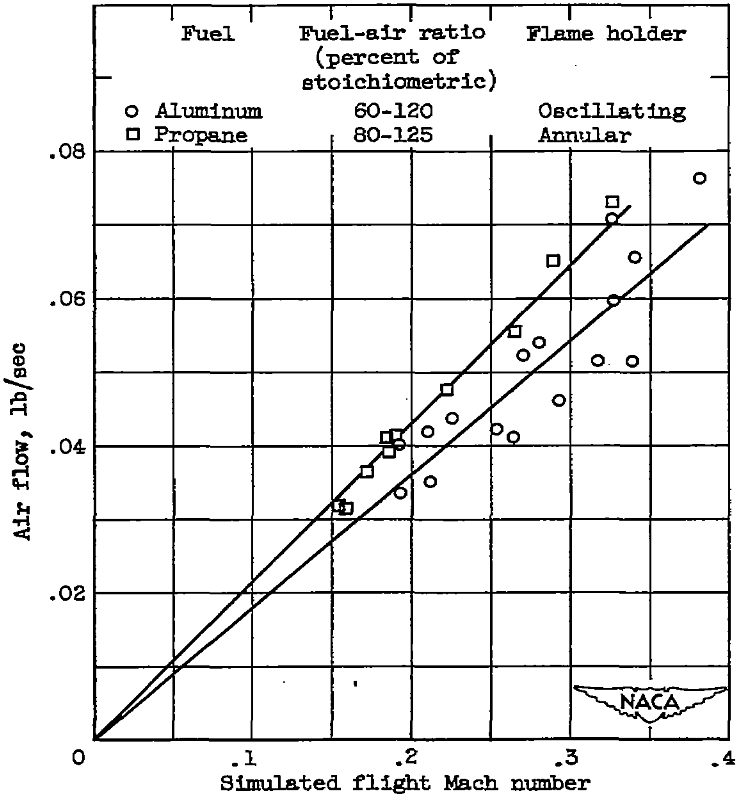
(b) Uniform flame in smooth combustion.

Figure 3. - Concluded. Flame emitted from combustor.



(a) Jet-thrust performance.



(b) Air-flow performance.

Figure 4. - Performance of aluminum-powder combustor fueled with aluminum and propane at sea-level conditions. Combustion-air velocity, 25 to 55 feet per second.

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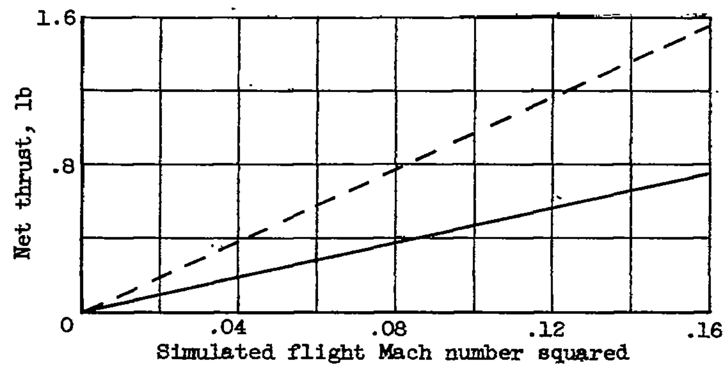
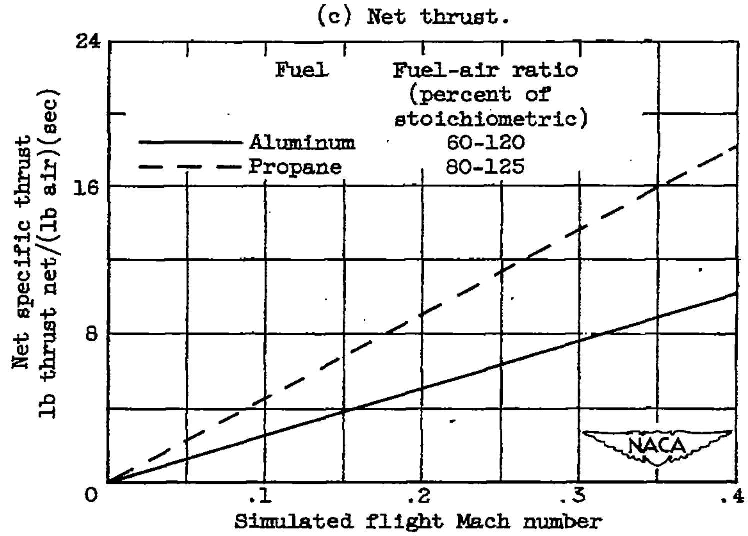
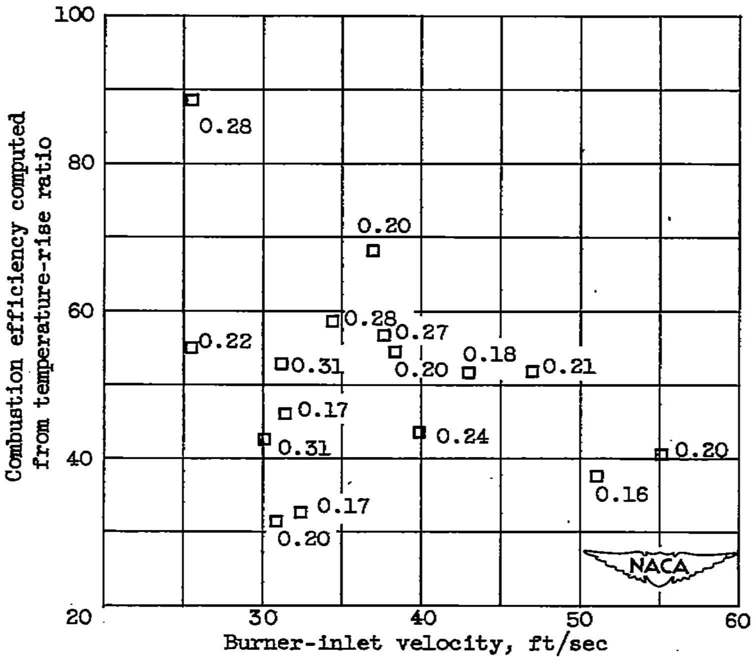


(c) Net thrust.



(d) Net specific thrust.

Figure 4. - Continued. Performance of aluminum-powder combustor fueled with aluminum and propane at sea-level conditions. Combustion-air velocity, 25 to 55 feet per second.



(e) Combustion efficiency of aluminum. (Values beside data points indicate fuel-air ratio.)

Figure 4. - Concluded. Performance of aluminum-powder combustor fueled with aluminum and propane at sea-level conditions. Combustion-air velocity, 25 to 55 feet per second.

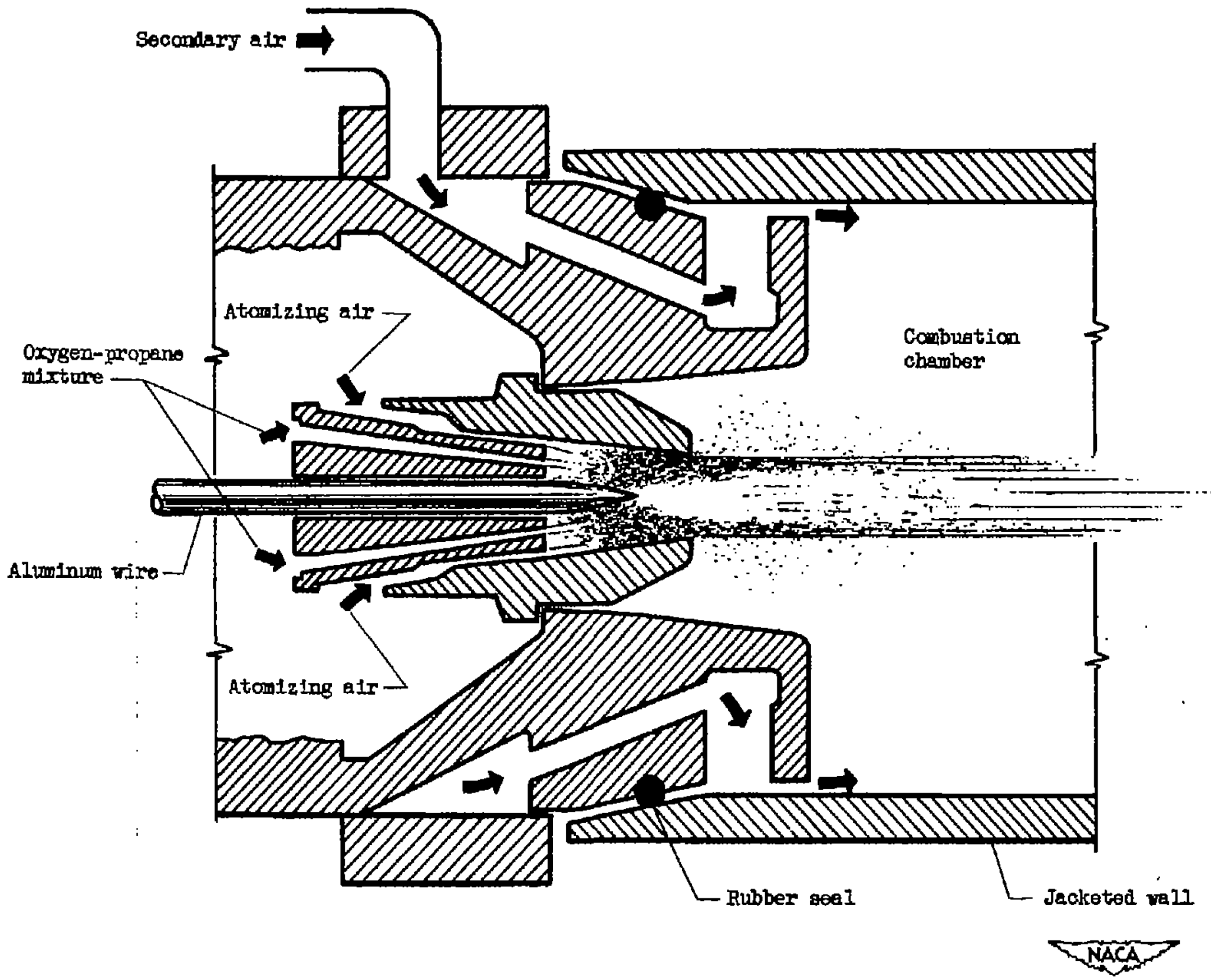


Figure 5. - Cross-sectional view of wire atomizer.

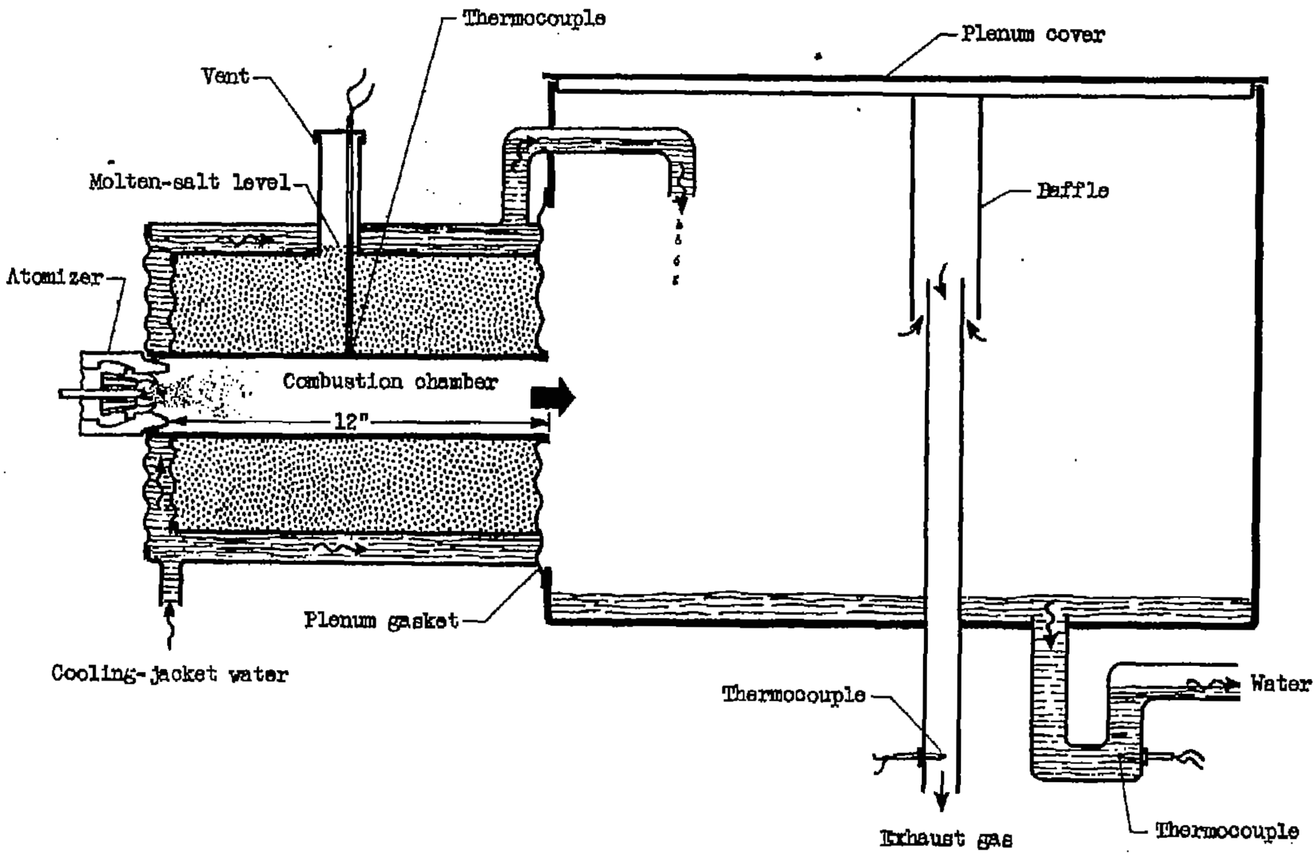


Figure 6. - Combustor and plenum chamber.

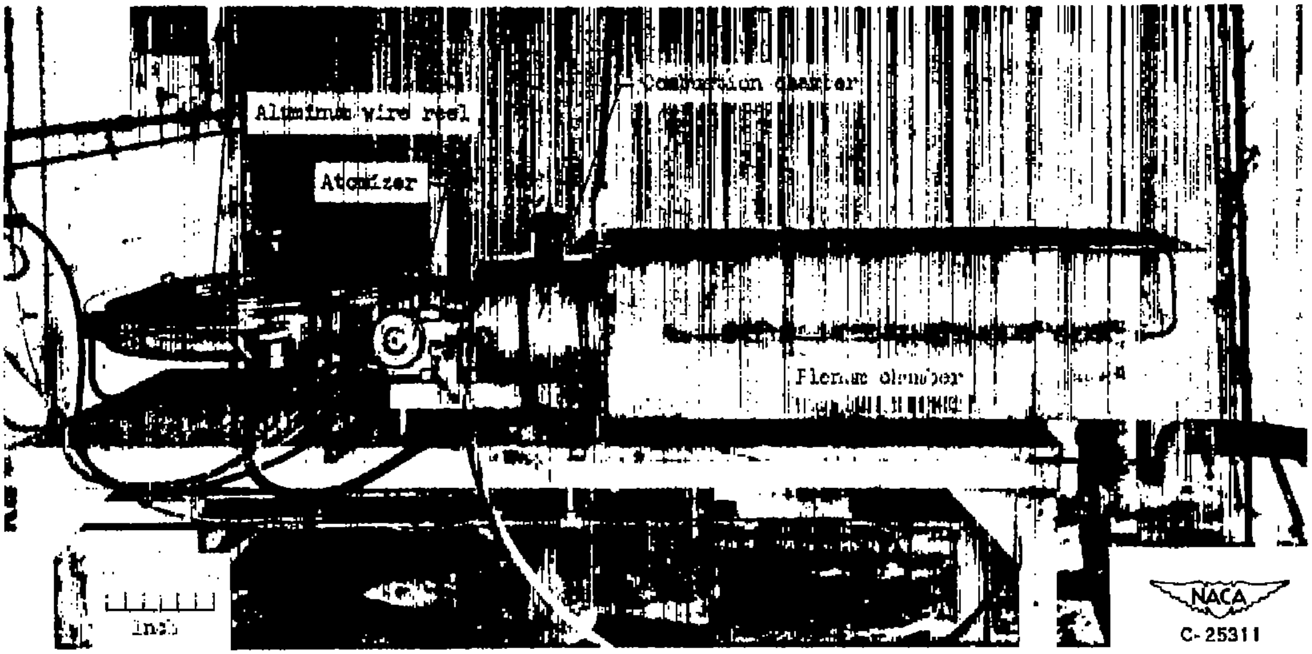


Figure 7. - Aluminum-wire combustor assembly.

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Figure 8. - Sectional view of wire combustion chamber after failure.

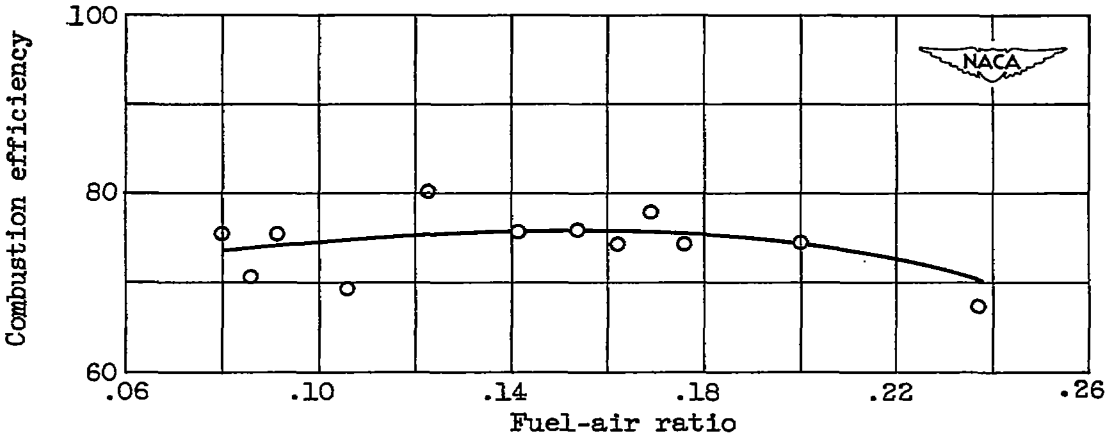

Figure 9. - Combustion efficiency of wire combustor as function of fuel-air ratio. Combustor-inlet pressure, 1 atmosphere; combustor-inlet temperature, 3000° F; combustor-inlet velocity, 115 feet per second.

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